Comparing phosphorus management strategies at a watershed scale

R. W. McDowell, A. N. Sharpley, D. B. Beegle and J. L. Weld

ABSTRACT. The persistence of water quality problems has directed attention toward reduction of agricultural non-point sources of phosphorus (P). We assessed the practical impact of three management scenarios of the USDA-EPA Strategy for Animal Feeding Operations to reduce P losses from a watershed. Using an agronomic threshold of 50 mg Mehlich-3 P kg^{-1} soil, 55% of our watershed would receive no P as fertilizer or manure. An environmental threshold of 190 mg Mehlich-3 P kg^{-1} soil, above which P loss in runoff increases, restricts future P inputs to less than crop removal on 32% of the watershed. Finally, a site assessment P index, which accounts for likely source and transport risks was used. This showed none of the watershed was at high risk of P loss and that areas of medium risk (where remedial measures should be considered) were near the stream channel. In the watershed studied, the P index was the best method to target remedial management to minimize P export and impacted less land area than the other strategies.

Keywords: Animal Feeding Operations, CAFO strategies, eutrophication, fertilizer management, manure management, nonpoint source pollution, nutrient management planning, phosphorus index, phosphorus runoff, risk assessment, water quality, watershed runoff.

Agriculture is increasingly linked to water quality concerns. Besides soil and pesticide loss from agriculture, most environmental concerns center on diffuse loss of phosphorus (P) and its role in accelerating freshwater eutrophication (Carpenter et al., 1998). The trend of increased fertilizer use in crop production over the last 50 years has fragmented farming systems, creating specialized crop and livestock operations that efficiently coexist in different regions within and among countries (Sharpley et al., 1998). This has created a surplus of P inputs in feed and fertilizer in these areas compared to outputs in primary production (Lanyon, 2000).

A major issue in manure management is whether nutrient management plans should be based on P or nitrogen (N) content. In many regions, including the state of Pennsylvania, manure application guidelines are based on balancing N inputs with crop requirements to minimize the need to purchase N fertilizers, and the risk of nitrate leaching into ground water. However the N/P ratio of manure is commonly 2 to 3.5 times less than that taken up by the crop (Eck and Stewart, 1995). Thus, when manures are spread on the land, soil P accumulates and increases the potential for P loss to surface waters (Sims et al., 1998; Sharpley and Tunney, 2000). In areas where more concentrated animal feeding operations occur, the situation may be more extreme, because it is uneconomical to transport large amounts of manure from surplus to deficit areas.

The ultimate goal of P management is to balance P inputs to farm with outputs in primary production such that no excess P is applied and soil P concentrations are kept at an optimum level for agronomic performance and minimal environmental impact. However, because of the potential for major changes in agricultural management and negative economic impacts, it is necessary to explore short-term or temporary fixes and methods while the longer term issues related to nutrient balance are addressed. This has led the USDA and EPA to devise a joint strategy for sustainable nutrient management for animal feedings operations AFOs (USDA-USEPA, 1999). This joint strategy proposes a variety of voluntary and regulatory approaches, whereby all AFOs develop and implement comprehensive nutrient management plans by the year 2008. These plans deal with manure handling and storage, application of manure to the land, record keeping, feed management, integration with other conservation measures, and other options for manure utilization. An important part of this joint strategy outlines how acceptable manure application rates will be determined in these plans. With this in mind, the joint strategy describes three options for developing appropriate P-based nutrient management plans; agronomic soil test P (STP) recommendations, environmental

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soil test P (STP) thresholds, and a P index to rank fields according to their vulnerability to potential P loss.

This focus of this paper is to compare each option in an experimental watershed in central Pennsylvania, USA for the development of a watershed scale integrated P-based management plan.

Methods and Materials

Study Site. The study was conducted on a 97.6 acre (39.5 ha) sub-watershed of Mahantango Creek (FD-36), a tributary of the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). The watershed is typical of upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian Valley and Ridge Physiographic Province. The dominant soils are loamy skeletal to fine loamy, mixed, mesic families of Typic Dystudepts (80% of the watershed) and Typic Fragiudults (20% of the watershed). Slopes within the watershed range from 1 to 20%. Climate is temperate and humid, with an average rainfall of 43 inches yr^{-1}.

The watershed is characterized by mixed land use typical of that found in the North East US (50% soybean, wheat or corn; 20% pasture; 30% woodland). Management of individual fields was obtained from annual farmer surveys (Table 1). Fertilizer application averaged about 27 lbs P ac^{-1} yr^{-1} to soybeans. Manured fields received differing rates, ranging from 27 tons ac^{-1} yr^{-1} pig slurry (approximately 67 lbs P ac^{-1} yr^{-1} and 270 lbs P ac^{-1} yr^{-1}) to 2.2 tons ac^{-1} yr^{-1} poultry manure (approximately 200 lbs P ac^{-1} yr^{-1} and 430 lbs P ac^{-1} yr^{-1}) (Eck and Stewart, 1995; Sharpley et al., 1998).

In May 2000, soil samples (0-2 and 0-6 inch depth) were collected on a 100-foot (30-m) grid over the watershed. Soil sampling depths for the agronomic soil test strategy was 0-6 inches and for the environmental soil P test threshold and P index strategy was 0-2 inches (Beegle, 1999; Sharpley et al., 1996). Samples were air dried, ground and sieved (< 2 mm) and STP determined using the Mehlich-3 P method (Mehlich, 1984). The Mehlich-3 extractable P data within each individual field were used to generate a mean concentration for the field, and used as the basis to test each management strategy (agronomic, environmental and the source factor components of the P index).

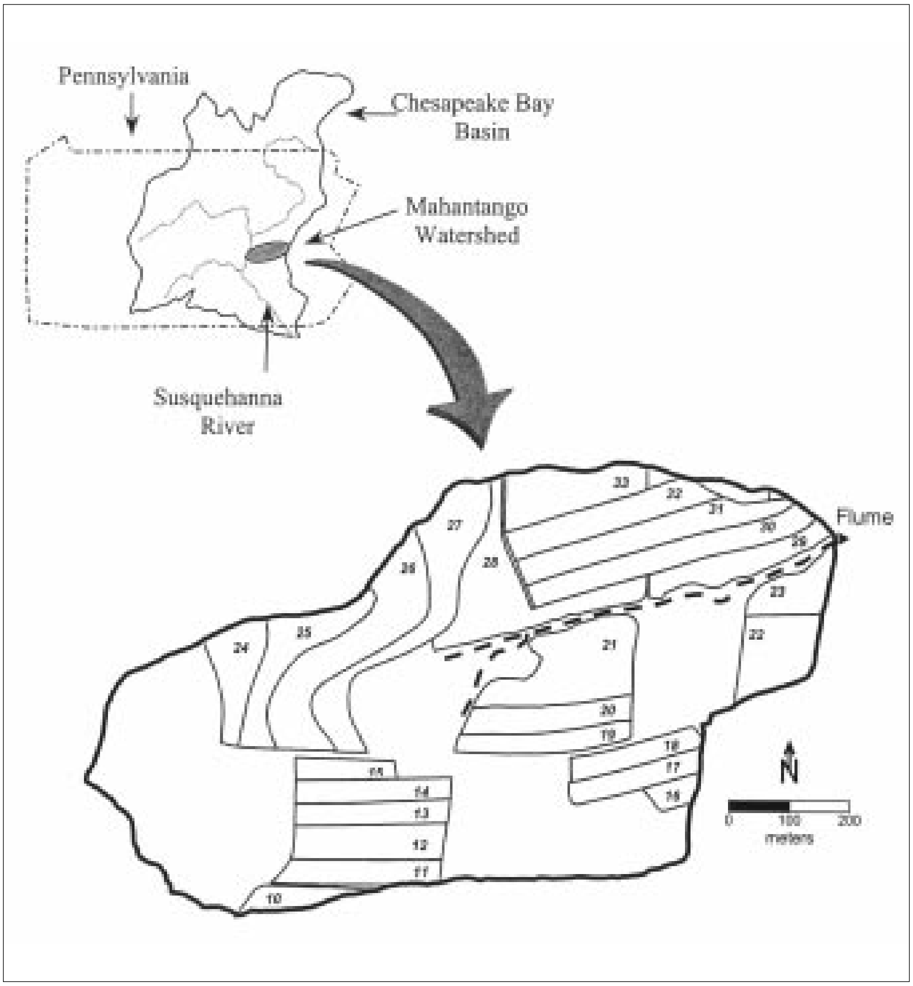

Figure 1. Location and fields within the experimental watershed (FD-36) in relation to the Chesapeake Bay Basin (adapted from Sharpley et al., 1998.)

Agronomic Soil Test Phosphorus Recommendation. In this option, manure application rates would be based on the recommendations for optimum crop production as detailed in the Pennsylvania soil test program (Table 2, soil test program). In other words, if the STP (0 - 6 inch depth) called for a P addition to grow the crop, manure could be applied only to supply the recommended P. If the STP did not recommend any P addition, little or no manure could be applied (Table 2, AFO guidance).

Environmental Soil Test Phosphorus Threshold. In this option, a STP concentration (based on a 0-2 inch sampling depth) is established above which the enrichment of P in agricultural overland flow becomes unacceptable (Sharpley et al., 1996). Using the AFO strategy for P threshold, little or no manure can be applied above the threshold in STP concentration (Table 3). The actual threshold levels (TH) will most likely be site specific and determined from research like that described below. This approach has a much stronger scientific basis for managing P to protect the environment than does the agronomic soil test option. First, sampling and extraction procedures are developed or adapted specifically for estimating P loss potential from the soil. Second, interpretations are developed based on standardized field calibration research relating the soil P level to P in overland flow.

However, a major difficulty with this approach is the identification of a threshold STP concentration to establish when STP becomes great enough to cause unacceptable P enrichment of agricultural overland flow. Table 4 gives examples from several states. Determining appropriate thresholds for a wide range of soils and environments is currently a very contentious and active research area (Sharpley et al., 1999b).

An approach for determining a threshold uses a split-line model that separates the relationship between STP and P in overland flow or subsurface drainage waters into two sections, one with greater P loss per unit increase in STP than the other (Heckrath et al., 1995; McDowell and Condron, 1999). McDowell and Sharpley (2001) and McDowell et al. (2001b) give a description and application of the split-line model to determine thresholds.

Table 1. Land use and management data by field for watershed FD-36, 1999.

Field number†	Field area	Crop	Fertilizer P applied	Fertilizer application method / date	Manure P applied	Manure application method / date	Mehlich-3 soil P	
							0-15 cm	0-5 cm
	acres		lbs ac^{-1}		lbs ac^{-1}		mg kg^{-1}	
10	1.04	Corn	50	Broadcast / April	0		120	400
11	1.73	Barley	15	Broadcast / March	0		145	220
12	2.30	Pasture	0		0		180	225
13	1.53	Barley	15	Broadcast / March	0		150	210
14	1.53	Corn	50	Broadcast / April	0		140	210
15	0.89	Barley	15	Broadcast / March	0		160	195
16	054	Corn	50	Broadcast / April	0		181	310
17	1.36	Corn	50	Broadcast / April	0		250	260
18	1.31	Pasture	0		0		300	305
19	1.53	Corn	65	Broadcast / April	0		20	290
20	1.90	Wheat	70	Broadcast / October	0		20	220
21	4.03	Corn	65	Broadcast / April	0		60	70
22	2.47	Corn	0		100	Broadcast / May-June§	50	215
23	1.51	Corn	0		100	Broadcast / May-June§	40	65
24	1.95	Corn	65	Broadcast / October	0		180	200
25	2.62	Wheat	65	Broadcast / April	0		260	295
26	4.94	Corn	70	Broadcast / October	0		280	290
27	4.77	Corn	65	Broadcast / April	0		70	235
28	4.07	Wheat	70	Broadcast / October	0		70	92
29	1.98	Corn	0		100	Broadcast / May-June§	70	225
30	3.11	Wheat	0		100	Broadcast / May-June§	80	180
31	3.06	Corn	0		60	Broadcast / April-May§	220	370
32	2.62	Corn	0		100	Broadcast / May-June§	180	190
33	2.64	Soybeans	0		60	Broadcast / April-May§	280	350

† Refer to Figure 1.
§ Pig manure applied.

Table 2. Summary of the soil test program and Animal Feeding Operations crop soil test strategy for Pennsylvania.

	Soil Test Program		Animal Feeding Operation Strategy	
Soil test category† (mg kg^{-1})	Interpretation	Recommendation	AFO Guidance	Typical maximum manure rates for a 125 bu acre^{-1} corn crop‡
Low < 30	P deficient, high probability of an economic response to P	P recommended to build soil P into the optimum range and maintain it there	Manure rates based on the N requirement of the crop	Dairy 40 ton acre^{-1} Swine 10,000 gal acre^{-1} Poultry 8 ton acre^{-1}
Optimum 30 - 50	P adequate, low probability of an economic response to P	P recommended to replace crop removal of P and maintain optimum soil P	Manure rates based on 1.5 x P removal by crop	Dairy 19 ton acre^{-1} Swine 3,300 gal acre^{-1} Poultry 1.4 ton acre^{-1}
High 50 - 100	P more than adequate, no crop response expected to P	No P recommended	Manure rates based on P removal by crop	Dairy 13 ton acre^{-1} Swine 2,200 gal acre^{-1} Poultry 0.9 ton acre^{-1}
Excessive > 100	P more than adequate, no crop response expected to P	No P recommended	No manure P applied	No manure applied

† Soil test P as Mehlich-3 P, mg kg^{-1}.

‡ Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application.

Table 3. Summary of the Animal Feeding Operations soil P threshold strategy for Pennsylvania.

Soil P threshold level	AFO guidance	Typical maximum manure rates for a 125 bu acre^{-1} corn crop†
< .75 TH < 150 mg kg^{-1}	Manure rates based on the N requirement of the crop	Dairy 40 ton acre^{-1} Swine 10,000 gal acre^{-1} Poultry 8 ton acre^{-1}
.75 TH to 1.5 TH 150 – 300 mg kg^{-1}	Manure rates based on P crop removal	Dairy 13 ton acre^{-1} Swine 2,200 gal acre^{-1} Poultry 0.9 ton acre^{-1}
1.5 TH to 2 TH 300 – 400 mg kg^{-1}	Manure rates based on 0.5 x P crop removal	Dairy 6.5 ton acre^{-1} Swine 1,100 gal acre^{-1} Poultry 0.45 ton acre^{-1}
> 2 TH > 400 mg kg^{-1}	No manure P applied	No manure applied

† Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application.

Recent research has shown thresholds occur at the same STP concentration when plotting STP against P in 0.01*M* $CaCl_2$ extracts (0-2 inch depth), overland flow, or sub-surface drainage water (McDowell and Sharpley, 2001; Hesketh and Brookes, 2000; McDowell et al., 2001a,b; Fig. 2). Using this method, it is possible to define a threshold expressed in STP concentration above which the potential for P loss increases significantly. An environmental threshold of 190 mg Mehlich-3 extractable P kg^{-1} was used in this study (Fig. 2).

The Phosphorus Index. In this option, an index is used to define areas within the landscape that contribute to P losses to surface waters so that management of P applications and/or remedial efforts can be better targeted. It is recognized today that not all areas on a landscape contribute equally to P losses, and that the majority of losses come from a small area in most watersheds and result from only a few storm events (Gburek et al., 2000; Heathwaite et al., 2000). For P losses to occur there must be a P source and a mechanism to transport it to surface water. Thus, effective environmental management of P losses requires information on where these two factors overlap. Preventing P loss should then concentrate on defining, targeting, and remediating source-areas of P with high STP concentrations only when they coincide with high overland flow and erosion potentials.

A simple P index has been developed by USDA-NRCS in cooperation with several research scientists as a screening tool for use by field staffs, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in overland flow (Lemunyon and Gilbert, 1993). The index accounts for and ranks source and

Table 4. Threshold soil test P values and P management recommendations (adapted from Lory and Scharf, 2000; Sharpley et al., 1996)

State	Environmental soil P threshold mg kg^{-1}	Soil test P method	Management recommendations for water quality protection
Arkansas	150†	Mehlich-3	At or > 150 mg P kg^{-1}: apply no P, provide buffers next to streams, overseed pastures with legumes to aid P removal, and provide constant soil cover to minimize erosion.
Colorado	100	Olsen	> 100 mg P kg^{-1}: hog producers with > 80,000 lbs capacity, no P applied unless overland flow is minimal.
Delaware	50	Mehlich-1	> 50 mg P kg^{-1}: apply no more P until soil is significantly decreased.
Idaho	50 & 100	Olsen	Sandy soils > 50 mg P kg^{-1}: Silt loam soils > 100 mg P kg^{-1}: Apply no more P until soil P is significantly decreased.
Kansas	100 - 200	Bray-1	Regions of the state coincide with high (eastern) to low (western) overland flow. Swine producers must eliminate manure applications above the threshold.
Ohio	150	Bray-1	> 150 mg P kg^{-1}: decrease erosion and/or eliminate P additions.
Oklahoma	130	Mehlich-3	30 - 130 mg P kg^{-1}: half P rate on slopes > 8%. 130 - 200 mg P kg^{-1}: half P rate and adopt measures to decrease overland flow and erosion. > 200 mg P kg^{-1}: P rate not to exceed crop removal.
Maine	40 - 100	Morgan	In sensitive watersheds apply no P above 40 mg P kg^{-1} and in non-sensitive watersheds apply no P above 100 mg P kg^{-1}.
Maryland	75	Mehlich-1	Use P index > 75 mg P kg^{-1}: soils with high index must reduce or eliminate P additions.
Michigan	75	Bray-1	75 - 150 mg P kg^{-1}: P application should equal crop removal. > 150 mg P kg^{-1}: apply no P from any source.
Mississippi	70	Lancaster	> 70 mg P kg^{-1} no P added
Texas	200	Texas A&M	> 200 mg P kg^{-1}: P addition not to exceed crop removal
Wisconsin	75	Bray-1	< 75 mg P kg^{-1}: rotate to P demanding crops and decrease P additions. > 75 mg P kg^{-1}: discontinue P additions.

† Agronomic threshold concentrations are average values for non-vegetable crops; actual values vary with soil and crop type. Also, vegetables have higher agronomic P requirements.

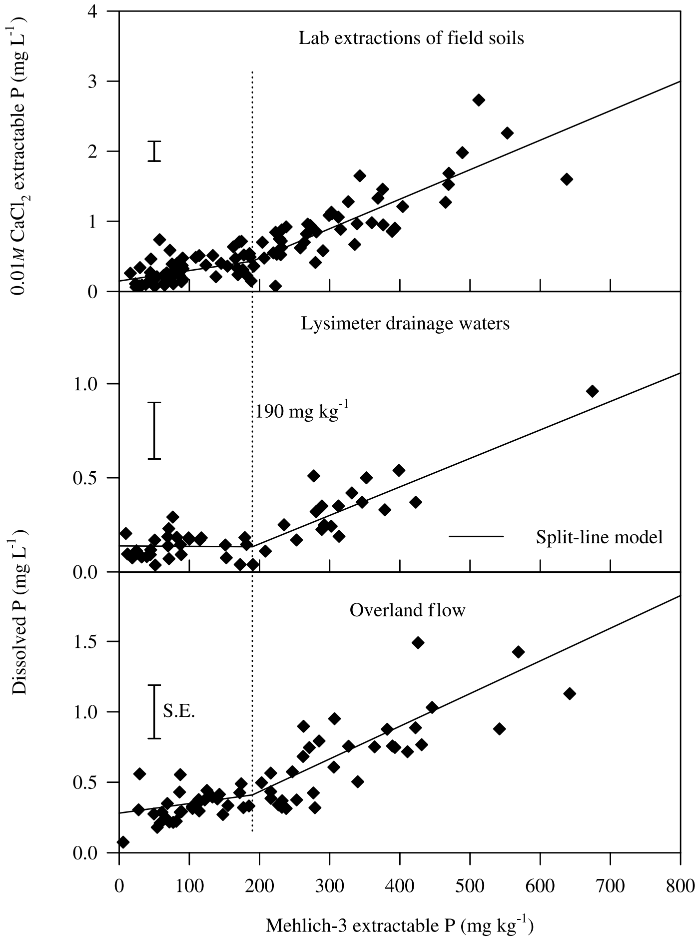

Figure 2. The relationship between Mehlich-3 extractable P of surface soils (0-5 cm) and dissolved P in overland flow, subsurface drainage from 30 cm deep lysimeters and 0.01M CaCl2 extractable P (0-5 cm) for soils in a central PA watershed (adapted from McDowell and Sharpley, 2001; McDowell et al., 2001a,b). The dashed vertical line represents the common value of the threshold at 190 mg Mehlich-3 extractable P kg^{-1}. S.E. is the standard error.

transport factors controlling P loss in overland flow and identifies sites where the risk of P movement is expected to be higher than that of others. Each site characteristic affecting P loss is weighted, by assuming that certain characteristics have a relatively greater effect on potential P loss than others. Each user must establish a range of P loss potential values for different geographic areas.

An assessment of site vulnerability to P loss in overland flow is made by selecting rating values for individual transport (Table 5) and site management factors (Table 6) from the P index. A P index value, representing cumulative site vulnerability to P loss from each site, is obtained by multiplying summed transport, source and management factors (Table 7). The P index values are scaled so that the break between high and very high categories is 100. This is done by calculating a site P index value, assuming all transport and source factors are high (erosion is set at 3.12 tons acre^{-1} (7 Mg ha^{-1}) considered a high value for Pennsylvania and soil test P is set at 200 mg kg^{-1} Mehlich-3 P proposed as a non-site specific threshold for Pennsylvania). The break between medium and high and low and medium is calculated using the same method and STP concentrations of 50 and 30 mg Mehlich-3 P kg^{-1} respectively. These coincide with the AFO joint strategy for a manure P applications based on crop removal (> 50 mg Mehlich-3 P kg^{-1}) and N-based manurial applications (< 30 mg Mehlich-3 P kg^{-1}). The AFO guidance based on the joint USDA-EPA strategy for the P index option is outlined in Table 8.

The index is a tool for farmers, consultants, extension agents, and livestock producers to help identify agricultural areas or practices that have the greatest potential to accelerate eutrophication. It will identify management options available to land users that will allow them flexibility in developing remedial strategies. Determination of a P index value for a site is the first step to prioritize the efforts need-

Table 5. Phosphorus loss potential due to transport characteristics in the PA P index (Part A).

Transport factor	Relative ranking					Field value
Soil erosion	Soil loss (ton ac^{-1} yr^{-1})					
Overland flow class	0 Very Low	1 Low	2 Medium	4 High	8 Very High	
Leaching potential	0 Very Low	0 Low	1 Medium	2 High	4 Very High	
Connectivity	0 Not connected†	1	2 Partially connected‡	4	8 Connected*	
					Sum transport factors / 27	

† Field is far away from water body. Overland flow from field does not enter water body.

‡ Field is near, but not next to water body. Overland flow from the field sometimes enters water body, e.g., during large intense storms.

*** Field is next to a body of water. Overland flow from field always enters water body.**

Table 6. Phosphorus loss potential due to source and management practices in the PA P index (Part B).

Source factor	Relative ranking					Field value
Soil test P	**Soil test P (mg P kg^{-1} soil)**					
STP rating value	Soil test P × 0.2					
Fertilizer P rate	**Fertilizer rate (lbs P ac^{-1})**					
P fertilizer application method and timing	Placed with planter or injected > 2 inch deep 0.2	Incorporated < 1 week after application 0.4	Incorporated > 1 week or not incorporated following application in late spring to early autumn 0.6	Incorporated > 1 week or not incorporated following application in late autumn to early spring 0.8	Surface applied on frozen or snow covered soil 1.0	
Fertilizer rating value	Fertilizer P application rate × Loss rating for fertilizer P application method and timing					
Manure P rate	**Manure application (lbs P ac^{-1}) ¶**					
P manure application method and timing	Placed with planter or injected > 2 inch depth 0.2	Incorporated < 1 week after application 0.4	Incorporated > 1 week or not incorporated following application in late spring to early autumn 0.6	Incorporated > 1 week or not incorporated following application in late autumn to early spring 0.8	Surface applied on frozen or snow covered soil 1.0	
Manure rating value	Manure P application rate × Loss rating for manure P application method and timing					
					Sum source factors	

Table 7. Worksheet and generalized interpretation of the P index and manure management.

To solve for P loss rating – add all numbers on Part A and selected numbers on Part B. Write these numbers on the worksheet. Multiply Part A × Part B. This is your final P loss rating.

Part A Value: __________

Part B Value: __________

Multiply A × B = ____________ = ____________ P Index Rating

P index	Interpretation of the P index
Low < 60	**LOW** potential for P loss. If current farming practices are maintained there is a low probability of adverse impacts on surface waters. Manure applications are based on N content.
Medium 60 - 80	**MEDIUM** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss. Manure applications are based on N content.
High 80 - 100	**HIGH** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and P management plans are needed to minimize the probability of P loss. Manure applications limited to P removed.
Very high > 100	**VERY HIGH** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss. No manure is applied.

ed to reduce P losses. Then management options appropriate for soils with different P index ratings can be implemented. Some general recommendations are given in Table 7; however, P management is very site-specific and requires a well-planned, coordinated effort between farmers, extension agronomists, and soil conservation specialists.

Results and Discussion

Agronomic Soil Test Phosphorus Thresholds. Soil test P, measured as Mehlich-3 extractable P on 0-6 inch samples, ranged from 7 to 300 mg kg^{-1} over the watershed, and was generally distributed as a function of land use and field boundaries. Soils in wooded areas had small Mehlich-3 extractable P concentrations (< 10 mg kg^{-1}), while cropped fields receiving manure and fertilzer applications were, in most cases, in excess of optimum crop requirements at 50 mg Mehlich-3 extractable P kg^{-1}. Near stream areas

(< 100-ft from stream channel) that were wet for much of the year, generally had Mehlich-3 P concentrations < 50 mg kg^{-1}, reflecting their limited productive value (unless drained) and thus small P additions.

Using the first management strategy using an ‘agronomic recommendation’, future manure additions are stopped in those fields with a mean STP concentration greater than that required for optimum crop growth, i.e., > 50 mg Mehlich-3 extractable P kg^{-1} (Table 2). Over the managed part of the watershed, 90% of the soils had Mehlich-3 extractable P concentrations at or greater than 50 mg kg^{-1} and 55% had concentrations > 100 mg kg^{-1} (Fig. 4, Table 9). If P additions were restricted by an agronomic recommendation only 4% of the entire watershed would be eligible (Fig. 4, Table 9).

In addition to being restrictive in terms of limiting future P applications, there are a number of problems with using the agronomic threshold approach. The most important is that soil test sampling, extraction, and interpretations were developed strictly based on crop response. In the process of developing the soil test program, no environmental P loss potentials were measured (Beegle, 1999). Therefore, there is no scientific basis for assuming that the agronomic soil test based on crop response will be correlated with environmental impact. Also, this option only measures plant-available P. It does not reflect P that is potentially available in overland flow or to soil solution percolating down the soil profile.

Sampling depths can also be problematic. For routine soil fertility evaluation and recommendations, soil samples are usually collected to ‘plow depth’, or the zone of greatest root concentration, e.g., 0 - 6 inches deep. However, for example when soil testing is used to estimate P loss in overland flow, it is the surface soil (0 - 2 inches) that comes into contact with overland flow water that is sampled. To overcome such limitations, agronomic data is being used now as a base from which data from new testing methods can be incorporated in the future to give an environmental threshold.

Environmental Soil Test Phosphorus Threshold. Assuming an environmental soil P threshold (0-2 inch depth) of 190 mg kg^{-1} (Table 3, Fig. 2), 87% of the total watershed area and 77% of the managed (cultivated and pasture) land has STP concentrations above this value. Using the AFO strategy outlined in Table 3, 18% of the managed area of the watershed would be subject to manure applications based on the N requirements of the crop (Fig. 4, Table 9). Reduced manure applications based on crop P removal and half crop P removal would apply to 51% and 30% of the managed area of the watershed respectively, while no P would be allowed on only 2% (Fig. 4, Table 9).

Table 8. Summary of the Animal Feeding Operations P index strategy for Pennsylvania.

P index risk rating	AFO guidance	Typical maximum manure rates for a 125 bu $acre^{-1}$ corn crop†
Low < 60	Manure rates based on the N requirement of the crop	Dairy 40 ton $acre^{-1}$ Swine 10,000 gal $acre^{-1}$ Poultry 8 ton $acre^{-1}$
Medium 60 - 80	Manure rates based on the N requirement of the crop	Dairy 40 ton $acre^{-1}$ Swine 10,000 gal $acre^{-1}$ Poultry 8 ton $acre^{-1}$
High 80 - 100	Manure rates based on P crop removal	Dairy 13 ton $acre^{-1}$ Swine 2,200 gal $acre^{-1}$ Poultry 0.9 ton $acre^{-1}$
Very High > 100	No manure P applied	No manure applied

† Uses book values for crop requirement and manure nutrient content (swine is grower pigs, poultry is layers). Assumes spring application with incorporation by tillage or rain 2-5 days after application.

The difference between agronomic and environmental thresholds is illustrated in Fig. 3. The critical level for crop response is the point on the dashed line in Fig. 3 where the yield no longer increases as STP concentrations increase. The environmental threshold P is the STP concentration on the solid line where the potential environmental impact becomes unacceptably large. Even if the same soil test extractant is used, it cannot be assumed that there is a direct relationship between the soil test calibration for crop response to P and P loss potential. What will be crucial in terms of managing P based in part on STP concentrations, will be the interval between the threshold soil P value for crop yield and overland flow P (Fig. 3).

The critical soil test level for P loss may be above or even below the critical level for crop yield. However, data is beginning to show that in most cases the environmental threshold in STP is above that required for optimum crop growth. For example, in addition to the environmental threshold established for the current study site, the soil of the Broadbalk Continuous Wheat Experiment at Rothamsted (Harpenden, U.K.) has a threshold (termed a change point) at 55 mg kg^{-1} bicarbonate extractable or Olsen P (Heckrath et al., 1995). This is well above 25 mg Olsen P kg^{-1}, the concentration required for the optimum growth of potatoes, sugar beet, winter wheat and spring barley (Johnston and Poulton, 1997).

Although the environmental threshold is less restrictive to farmers in terms of future P applications, it does require additional tests to assess the potential for P loss (e.g., P extractable in 0.01*M* $CaCl_2$ or water; Hesketh and Brookes, 2000, Mc-

Table 9. Area of the managed portion of the watershed impacted by the various P management strategies.

P recommendation	P management strategy: Current	Agronomic soil test P	Environmental soil P threshold	P index
	acres			
N based	55.1	3.5	9.6	48.9
1.5 × Crop Removal	0	4.0	0	0
1.0 × Crop P removal	0	17.8	27.9	6.2
0.5 × Crop Removal	0	0	16.5	0
No P applied	0	30.1	1.0	0

Dowell and Trudgill, 2000). If soil tests are to be interpreted for the probability of P loss, calibrations that specifically relate the soil test to some measure of environmental response, such as P in overland flow, will be necessary. Unfortunately, even though this currently is a very active research area, a clear consensus has not been reached on interpreting soil P tests for environmental purposes (Sharpley et al., 1999b). Most agree that it is not likely that there will be one critical soil test level for P loss potential. Indeed the threshold established in for the soils in this watershed at 42 mg Olsen P kg^{-1} is smaller than that established from the Broadbalk Continuous Wheat Experiment at Rothamsted at 55 mg Olsen P kg^{-1} (Harpenden, U.K.); assuming Mehlich-3 P is 4.5 times Olsen P, $r^2 = 0.88$, $p < 0.001$, $n = 300$ (unpublished data). It is more likely that an integrated approach, including many other site-specific factors, will be necessary for environmental risk assessment of a given field.

The Phosphorus Index. Applying the third management strategy a ‘P index’ to the FD-36 watershed (Table 5-7), identifies different areas of the watershed that represent areas with sources of P and susceptible to transport. None of the watershed is defined as of very risk of P loss, however 6% of the total watershed area was defined as of ‘high’ risk (Fig. 4). These areas are where high soil P, manure and fertilizer application, and the risk of overland flow or erosion coincide. Using the P index option, P applications would be managed based on the N requirements of the crop over the entire watershed, except in 6.2 acres (2.5 ha) of land which would be managed according to the P requirements of the crop. The P index management strategy is the least restrictive of the three options to farmers when considering short-term P applications (Table 9). Future management to reduce P losses would need to target only 13 and 10% of the managed area of the watershed, deemed of a medium and high risk to P loss respectively (Fig. 4).

The small area of the watershed targeted for P management by the P index (23%) compared to agronomic (90%) and environmental (82%) STP strategies, is consistent with measured P loss from FD-36. For example, the mean annual flow-weighted concentration of dissolved and total P in stream flow from FD-36 for 1996 to 1999, is 0.05 and 0.075 mg L^{-1}, respectively (Pionke et al., 1999; Sharpley et al., 1999a). These levels are below eutrophic criteria (0.1 mg L^{-1} as total P) established for stream or other flowing waters not discharging directly into lakes or impoundments (Dodds et al., 1998; USEPA, 1994). Based on the level of water quality impairment of FD-36, in terms of P loss criteria, there is little justification for major changes in P management at a watershed scale at the present time. Thus, the P-index strategy may be the most prudent management approach, given the relatively low concentration of P in stream flow, as long as targeted conservation measures reduce the potential for P loss during high-risk periods (e.g., storm flow and after land application of manure or fertilizer).

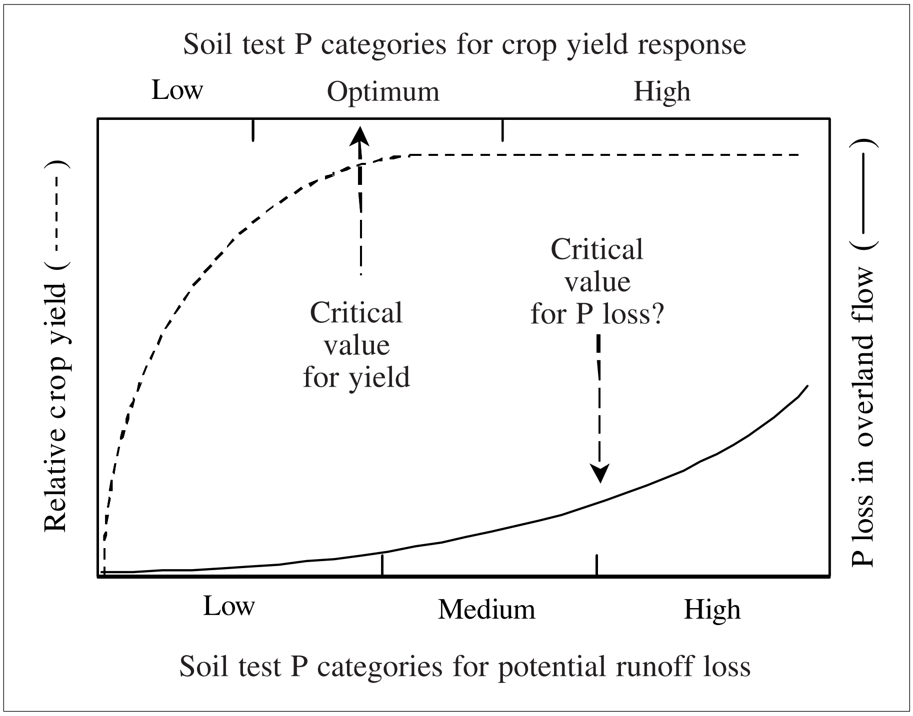

Figure 3. As soil P concentration increases so does crop yield and the potential for P loss in overland flow. The interval between the critical soil P concentration for yield and overland flow P will be important for P management.

Each of the three P-management strategies is intended to reduce the risk of P loss from a watershed. Clearly, there will be different impacts on farm operations depending on which option or strategy is adopted. Although these are hypothetical evaluations, information is needed on the actual impacts of implementing these P-management strategies on actual P loss from a watershed as well as farm production and economics. For example, what would be the impact on livestock operations and manure management in the studied watershed, FD-36, where poultry manure from an egg-laying operation and swine slurry from a pig farm are applied to several cropped fields in the watershed? Obviously, selection of the appropriate P-management strategy will impact these operations. Research is thus, needed on the effect of changing P management by these strategies on actual P loss from the watershed. In other words, would focusing P remedial efforts to the critical high risk areas on a small area, result in as great a reduction in P export as remediating P loss from the entire watershed? However, if P management is to be effective in minimizing P losses then work must be ongoing and regular assessments made of management strategies (e.g. redoing the P index every 2 years).

Summary and Conclusion

In some states, legislation has been introduced to base manure inputs on agronomic concentrations of soil P rather than manurial N content. If this is based on an environmental threshold, it is possible to identify fields with soil P concentrations with a much greater potential of contributing to P loss than if solely based on an agronomic threshold. Such an approach is more likely to be less restrictive to farmers and more technically defensible. However, these two management strategies ignore landscape variables that affect P transport, and therefore the susceptibility of fields to P loss. Prevention of P losses from watersheds should focus on defining, targeting and remediating fields that combine high soil P concentrations with areas of high erosion and overland flow potential. The measurement and

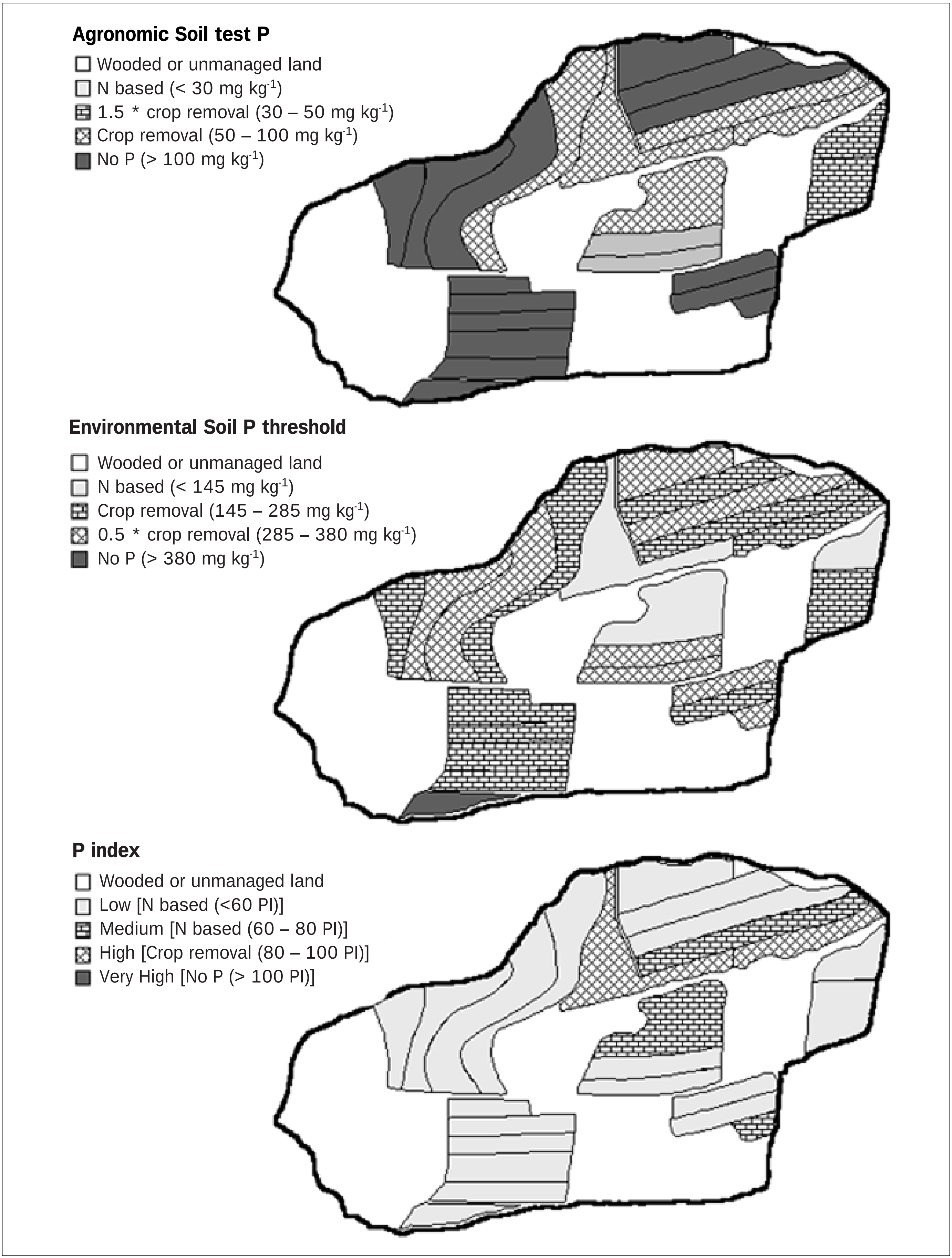

Figure 4. The experimental watershed (FD-36) under different management senarios.

integration of source and transport factors requires an understanding of P sources, soil properties, hydrologic conditions and crop management. Much work is required to better define the specific weightings within the P index to best estimate the major influencing factors and not allow one factor to wrongly mask another. However, control of P losses can only be achieved once P inputs in fertilizers, manures and feed have been balanced with outputs (e.g. primary produce) at the farm gate.

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